Historical glacier length changes in West Greenland

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Brief communication
"Historical glacier length changes in West Greenland"

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Abstract. Past glacier fluctuations provide insight into glacier dynamics, climate change, and the contribution of glaciers to sea-level rise. Here, the length fluctuations since the 19th century of 18 local glaciers in West and South Greenland are presented, extending and updating the study by Weidick (1968). The studied glaciers all showed an overall retreat with an average of 1.2 ± 0.2 km over the 20th century, indicating a general rise of the equilibrium line along the west coast of Greenland during the last century. Furthermore, the average rate of retreat was largest in the first half of the 20th century.

1 Introduction

Glacier length fluctuations are an indication of climate change as glaciers react with geometric adaptation to changes in climatic forcing (e.g. Oerlemans, 2001). Furthermore, the meltwater released due to the shrinkage of glaciers is the largest contributor to sea-level rise over the 20th century (Bindoff et al., 2007). Length fluctuations provide indirect evidence of changes in glacier mass balance, which is especially relevant near the margin of the Greenland ice sheet where long-term direct measurements of mass balance are scarce. The available long-term records of glacier terminus fluctuations can be used to put the recent retreat of glaciers on Greenland (Howat et al., 2008; Moon and Joughin, 2008; Kargel et al., 2012; Jiskoot et al., 2012; Mernild et al., 2012) into a historical perspective. In addition, glacier length fluctuations can be used to estimate the glacier contribution to sea-level change (e.g. Leclercq et al., 2011).

Until recently, the number of long-term glacier length records was very limited for the local glaciers on Greenland, i.e. glaciers not connected to the ice sheet (also referred to as glaciers and ice caps). Yde and Knudsen (2007) assessed glacier fluctuations during the 20th century on Disko Island, West Greenland. Their analysis is based on combining historical information from expedition reports and early maps with remote sensing data from aerial photography and Landsat images. Bjørk et al. (2012) reconstructed the length changes since the early 1930s of 132 local glaciers and outlet glaciers from the ice sheet in south-east Greenland from rediscovered aerial photographs, supplemented with satellite images.

By combining the observations of early investigators with aerial photography and own field observations, Weidick (1968) reconstructed the length fluctuations of over 80 local glaciers and 60 outlet glaciers of the ice sheet in south and West Greenland, between 60° and 72° N. Several of these records start in the middle or early 19th century, but they all end in the middle of the 20th century. When updated to present day, these records provide unique information of glacier fluctuations along the western margin of the Greenland ice sheet over the last one and a half century. Here, we present the updated records of length fluctuations for 18 of the local glaciers in south and West Greenland based on Weidick (1968). The 18 studied glaciers are clustered in three regions: Disko Island and Nuussuaq Peninsula between 69–72° N, Sukkertoppen around 66° N, and Julianehåb–Godthåb in the very south of Greenland at about 61° N (Fig. 1a). At

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present, all glaciers terminate on land, but seven glaciers were tidewater glaciers until the end of the 19th century or the beginning of the 20th century (Weidick, 1968).

2 Methods

We have used Landsat 7 ETM+, Landsat 5 TM, and aerial photography to update records of glaciers that have a long record, do not show signs of surging (frequently found in the Disko Island and Nuussuaq Peninsula region (Yde and Knudsen, 2005; Citterio et al., 2009), and for which the new glacier lengths could be related to the length records in Weidick (1968).

The glacier outlines were obtained from the Landsat scenes by automated techniques using the well-established band ratio method (e.g. Paul and Kääb, 2005) that classifies glaciers when the digital numbers in band 3 (red) are about two times higher than in band 5 (shortwave infrared). Afterwards, outlines were manually corrected for shading, seasonal snow, and debris cover. The pixel size of the Landsat images is 30 m, and the position of the outlines can be determined with a precision of about one pixel (Paul et al., 2012). The locations of the drainage divides strongly influence the total length of a glacier. They were automatically derived from watershed analysis using the ASTER GDEM digital elevation model (DEM) with 30 m horizontal resolution. Flow lines were manually drawn, based on the DEM and flow patterns visible on the satellite images. For the processing we used the ArcInfo geographic information system (GIS) software and the open source GRASS software. Glacier outlines of glaciers in the Disko and Nuussuaq region (no. 1–8 in Table 1) for 2001 are taken from Citterio et al. (2009). Here, we study only changes in glacier length; the glacier area is determined only for the year closest to 2000 (2002 for four glaciers in the southern region, 2001 for the glaciers in Disko and Nuussuaq region).

We have also included the digitized glacier outlines from the GEUS-PROMICE maps (Citterio and Ahlstrøm, 2012) and additional literature values. Within the study area the GEUS-PROMICE outlines are derived from aerophotogrammetric maps based on stereopairs mostly acquired in 1985, with a few glaciers having been photographed in 1962 or as early as 1953 (Table 1). The absolute map accuracy of the GEUS-PROMICE outlines depends on the ground control points used in the aerial triangulation, and on the scale of the aerial photographs (1 : 150 000 for the 1985 data). Before measuring glacier lengths from the GEUS-PROMICE maps, any local horizontal bias was removed by manually matching the flow line of each glacier with the flow line derived from the Landsat data. The spatial resolution of the aerial photographs is much higher than the Landsat pixel size, which remains the dominating source of uncertainty. Additional values of length variations were obtained from Gribbon (1970) for Sermikassak (older name: Sermikavsak),

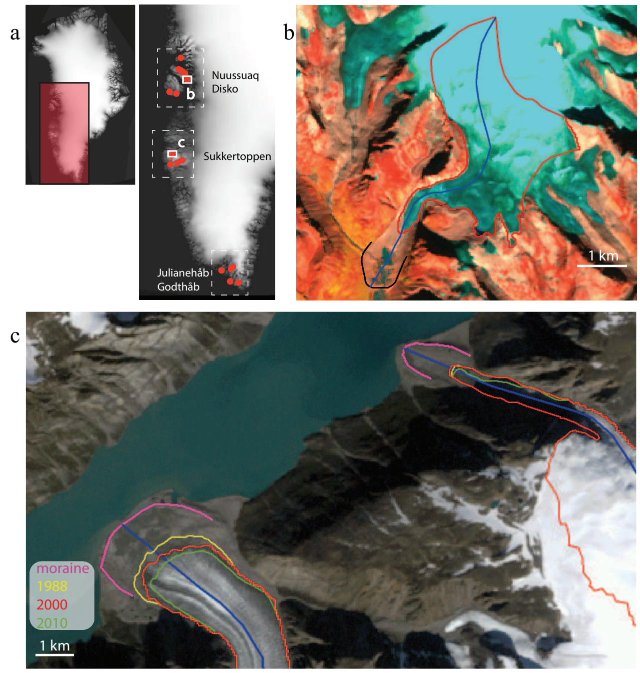

Fig. 1. **(a)** Location of the studied glaciers. White squares give the position of the images shown in **(b)** and **(c)**. **(b)** Glacier outlines in 2000 (red), flow line (blue), and maximum extent (black) of Saqqaq derived from Landsat imagery and DEM. Background is a false colour composite of the 2010 Landsat image. **(c)** Two examples, Serminnguaq (left) and Sissarissut (right), of frontal retreat measured from 3 Landsat images in 1988, 2000, and 2010. Background image is a colour composite of the 2000 Landsat scene.

from Yde and Knudsen (2007) for Tunorsuaq (older name: Tunorssuaq), and from Weidick (1988) for Narsap (older name Narssaq), Sermitsiaq and Napassorssuaq (older name Napassorssuaq). Weidick (1988) also gives values for the length changes of the Motzfeldt glaciers, glaciers that were not included in Weidick (1968).

In Weidick (1968) the length changes are expressed as distance between the glacier tongue position and the maximum extent along the flow line (cf. Fig. 8 and Table 2 in Weidick, 1968). For nine glaciers (6–10, 12, 14, 15, 17) this maximum extent can be identified on the Landsat images (Fig. 1b) with an accuracy comparable to that of the glacier outlines. For these glaciers, the length records were continued by measuring the distance between the maximum extent and the frontal positions determined along the flow line (Fig. 1c). It should be noted that this flow line is redefined, and therefore not strictly identical to the one used by Weidick (1968). For Sermikassak, Narsap, and Napasorssuaq, the 1953 aerial photograph used in the GEUS-PROMICE outlines is also included in the records of Weidick (1968). The 1953 extent is used as reference. For the remaining six glaciers, the Landsat observations could be connected to the existing record from the distance to the coastline. Weidick (1968) reports that

Table 1. Number, name, inventory numbers in Weidick et al. (1992) (inventory) and Weidick (1968) (loc no.), region, latitude (lat), longitude (long), glacier area (size), length along flow line (length), and years with information used for extending Weidick (1968): digitized glaciers outlines from aerial photography (aerial) and USGS Landsat images (Landsat). Glacier area and length are derived from the 2000, 2001, or 2002 glacier outlines. We have used the new Greenlandic spelling of the glacier names, which slightly differs from the old spelling used in Weidick (1968).

No.	name	inventory	loc no.	region	lat	long	size (km^2)	length (km)	aerial	Landsat
1	Sermikassak		119 IV	Nuussuaq	71.22	−53.96	22.46	14.25	1953	2001 2010
2	Assakaat Sermiat	1IB 26 003	109	Nuussuaq	70.52	−52.07	13.20	8.71	–	2001 2010
3	Sermiarsuit Sermikassaat	1IB 27 003	108	Nuussuaq	70.52	−52.15	20.33	11.31	–	2001 2010
4	Soqqaap Sermia	1IB 24 003	112	Nuussuaq	70.47	−51.88	15.46	8.92	1985	2001 2010
5	Umiartorfiup Sermia	1IB 25 002	110	Nuussuaq	70.47	−51.98	39.90	15.10	1985	2001 2010
6	Saqqaq	1GH 03 008	103	Nuussuaq	70.08	−51.70	8.83	6.18	1985	2001 2010
7	Akulliit	1HC 05 007	95	Disko Island	69.64	−54.50	3.43	2.89	1985	2001 2010
8	Tunorsuaq	1HA 04 009	85 B	Disko Island	69.32	−53.37	2.60	2.11	1985	2001 2010
9	Sissarissut	1DG 19 002	40	Sukkertoppen	66.37	−52.38	19.08	8.73	1985	1988 2000 2010
10	Serminnguaq	1DG 20 007	41	Sukkertoppen	66.28	−52.40	79.07	20.43	1985	1988 2000 2010
11	Qingua Kujalleq	1DF 22 002	56-1	Sukkertoppen	65.95	−51.92	57.00	15.11	1985	1988 2000 2009
12	Saarloq	1DF 32 002	53 1-N	Sukkertoppen	65.87	−52.61	4.27	3.99	1985	2000 2009
13	Kangiusaq	1DF 25 003	55	Sukkertoppen	65.85	−52.09	8.77	5.10	1985	2000 2009
14	Motzfeldt O	1AG 10 038		Julianehåb–Godthåb	61.15	−45.03	1.43	2.85	1962	1992 2002 2008
15	Motzfeldt V	1AG 10 039		Julianehåb–Godthåb	61.13	−45.09	6.11	4.75	1962	1992 2002 2008
16	Narsap Sermia	1AG 01 001	7	Julianehåb–Godthåb	60.99	−45.90	1.17	2.8	1953	1992 2000 2008
17	Sermitsiaq	1AB 06 008	1 A	Julianehåb–Godthåb	60.54	−44.16	23.80	11.48	1985	2002 2010
18	Napasorssuaq	1AC 18 002	2	Julianehåb–Godthåb	60.30	−45.27	1.97	2.64	1953	2002 2010

Assakaat and Soqqaap (older names: Assakiat and Sorquap, respectively) were near to or at the sea in 1893 and 1896, respectively. Sermiarsuit, Umiartorfiup, Qingua Kujalleq, and Kangiusaq (older names: Sermiarssuit, Umiartopfiup, Qingua Kujatdleq, and Kangiussaq, respectively) were calving glaciers in the 19th century, but all retreated on land during the period of their observations in Weidick (1968). The year of retreat on the coast line and the distance to the maximum extent are not exactly known. However, the resulting uncertainty in the coupling of the Landsat results to the record of Weidick (1968) is small: the retreat between the last observation of calving and the first time the glacier front was on land is about 10 to 100 m for these four glaciers. We assume the changes in the position of the coast line are negligible with respect to the uncertainties in the position of the glacier front.

3 Results and discussion

The records cover the 20th and part of the 19th century, starting between 1811 and 1900 (on average in 1853) and ending in recent years (2008–2010) (Fig. 2a). The number of data points per record varies between 6 and 13, with a mean of 10 observations per record. The data points before 1900 rely mostly on interpretation of historical documents (see Weidick, 1968, for more details) and therefore have a larger uncertainty than the more recent data points that are derived from field work, aerial photography and satellite images.

Predominantly, the studied glaciers show little change in the 19th century, followed by a period of retreat in the 20th and 21st century, although a few minor re-advances are observed. The mean 20th century retreat is 1.2 ± 0.2 km ($12\,\mathrm{m\,a^{-1}}$), varying from 7 ± 400 m (Saarloq) to 2.7 ± 0.2 km (Soqqaap). The large spread in retreat reflects the large differences between the glaciers. The sample includes glaciers of different size and geometries; the glacier area varies from 1.2 to 79 km^2 and glacier length from 2.8 km to 20 km (Table 1). Furthermore, the average glacier retreat during the 20th century is smaller for the five glaciers in the Sukkertoppen region than for the glaciers in the other two regions, but the sample is too small for conclusions on general regional differences.

The average rate of length change in the 19th century is limited; it varies between -4.5 and $+4\,\mathrm{m\,a^{-1}}$. The first half of the 20th century shows the highest rates of retreat of the period covered by the records, peaking at an average of $22\,\mathrm{m\,a^{-1}}$ (with a standard deviation of $19\,\mathrm{m\,a^{-1}}$) during the period 1930–1939 (Fig. 2b). The average rate of change increases in the second half of the 20th century, but is negative throughout the entire century. During the first decade of the 21st century, all 18 glaciers retreat, and the average retreat rate increases to $11\,\mathrm{m\,a^{-1}}$ (with a standard deviation of $9\,\mathrm{m\,a^{-1}}$).

These results are in agreement with Yde and Knudsen (2007), who found an average retreat of $8\,\mathrm{m\,a^{-1}}$ for the non-surging glaciers on Disko Island over the period 1953–2005. Kargel et al. (2012) also found predominant retreat of glaciers in East Greenland of $10\,\mathrm{m\,a^{-1}}$ and $20\,\mathrm{m\,a^{-1}}$ for land-terminating and marine-terminating glaciers, respectively, over the period 2002–2009. Looking at changes in local glaciers in East Greenland over a longer period (1972–2011 and 1980s–2005), Mernild et al. (2012) and Jiskoot et al. (2012) found that the rate of glacier retreat as well as the fraction of retreating glaciers increased in the first decade

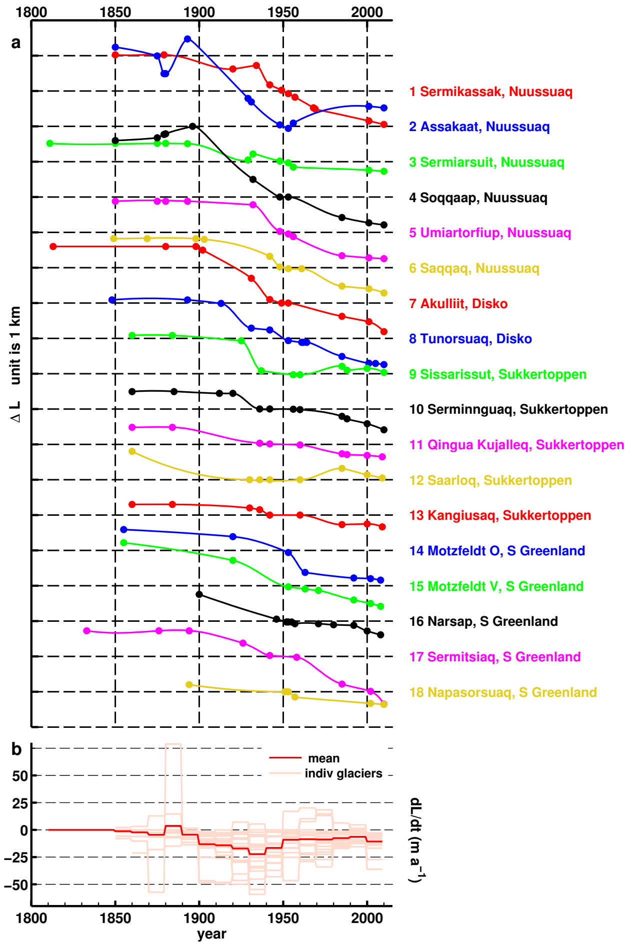

Fig. 2. (a) Length records of studied glaciers in West Greenland. Each dot represents a data point. Data are interpolated using Stineman interpolation (Stineman, 1980). To record 1, data from Gribbon (1970) were added; to record 8, data from Yde and Knudsen (2007); and to records 14, 15, 16, 17, and 18, data points from Weidick (1988) were added. **(b)** Rate of length change (ma^{-1}) averaged over 10-yr intervals in the period 1800–2010 for each of the glaciers (light coloured lines) and their average rate of length change (red).

of the 21st century compared to the previous decades. Our results for West Greenland show a comparable trend, and therefore we conclude that the glacier behaviour in West and East Greenland has been very similar over the last decades.

In addition, we have found a pronounced glacier retreat during the first half of the 20th century, with an average retreat rate in the 1930s that is higher than that of any other decade from the mid-19th century to 2010, the period covered by this study. Bjørk et al. (2012) also showed rapid retreat of local glaciers in south-east Greenland during the 1930s. This suggests that this is a period of widespread rapid retreat for a large part of Greenland's glaciers, which might be caused by a strong temperature increase during the 1920s and 1930s (Weidick, 1968). However, the length fluctuations are a delayed and filtered representation of surface mass balance variations. Therefore, the fact that retreat rates are largest in the beginning of the 20th century does not necessarily imply that surface mass balances in this period are the most negative of the entire period 1811–2010.

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